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DESPIN OF A HIGHLY SPINNING OBJECT: DESPIN OF THE ARMY'S UNATTE--ETC(U)

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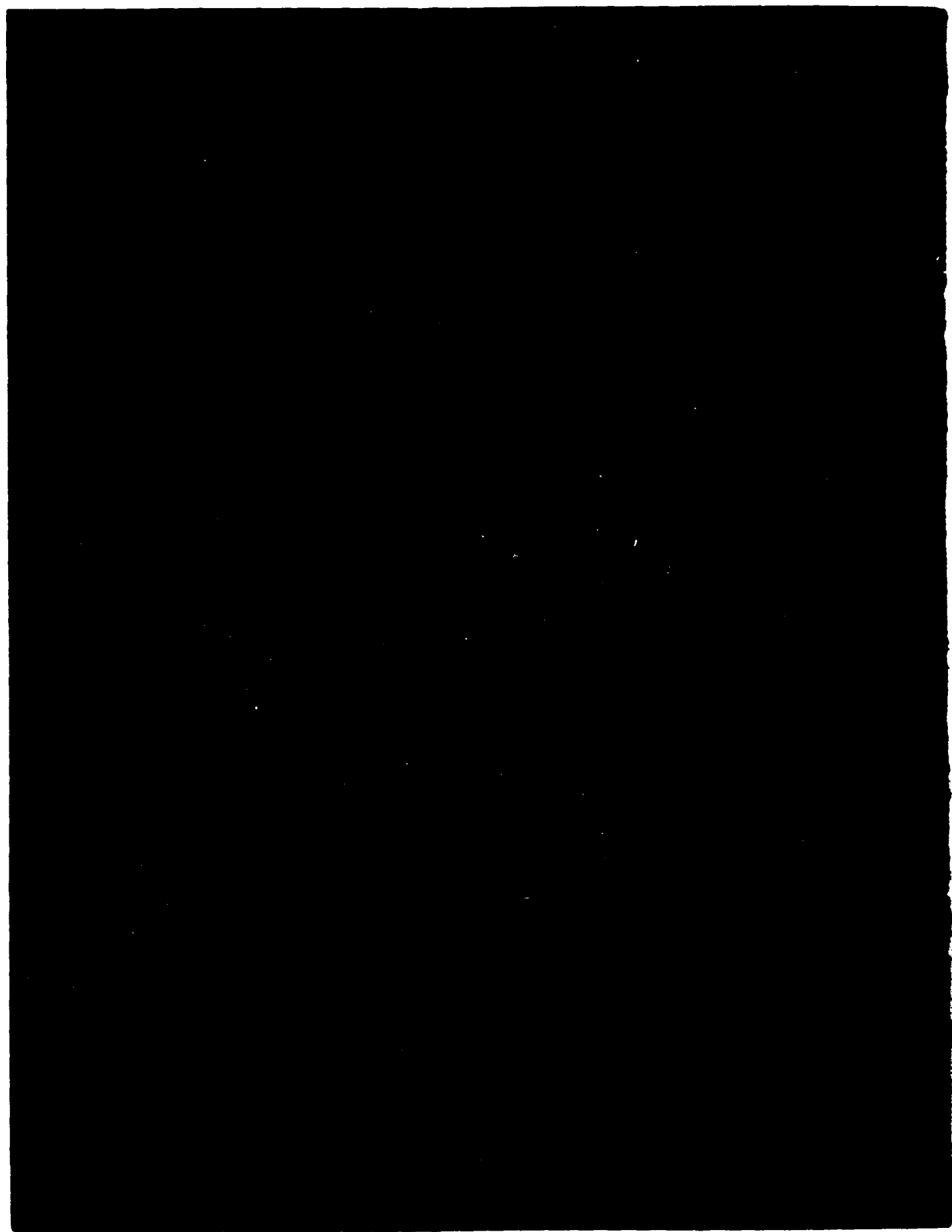
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A procedure, apparatus, and theoretical and test data are described for the partial and complete despin of a model unattended expendable jammer (UEJ) consisting of a circular disc of 8.9-lb (4.0-kg) weight, 2.5-in. (6.4-cm) radius, and 3.5-in. (8.9-cm) depth by using a single pair of yos. Each pair of yos consisted of Kevlar cords with either aluminum or brass weights. The results of camera and tachometer measurements of despin are presented for a total of 12 tests with initial spins in the range of 50 to 57 rps. The time for complete despin varies inversely with the initial spin velocity, and the time for despin in the present tests amounted to 20 ms for an initial spin velocity of 55 rps. Based on the presented calculations and scaling the measured test repeatability of initial spins in the range of 50 to 57 rps, a single pair of yos is		

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Item 20. Abstract (Cont'd)

believed capable of despinning the UEJ to within 3 rps of zero spin from any initial spin up to a required 260 rps.

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CONTENTS

	<u>Page</u>
SYMBOLS	5
1. INTRODUCTION	7
2. THEORETICAL CONCEPTS	7
3. EXPERIMENTAL APPARATUS	13
4. THEORETICAL AND EXPERIMENTAL RESULTS	16
5. SUMMARY AND CONCLUSIONS	16
DISTRIBUTION	19

FIGURES

1. Yo-yo despin device and unattended expendable jammer before despinning	7
2. Yo-yo despin device and unattended expendable jammer at time of release of yos	7
3. Notation for energy and momentum conservation equations	8
4. Predicted variation with ratio of initial to final spin velocities, $D = 0.06 \text{ lb}_F/\text{in.}^3$	10
5. Predicted variation with ratio of initial to final spin velocities, $D = 0.12 \text{ lb}_F/\text{in.}^3$	11
6. Predicted variation with density of Kevlar	12
7. Model unattended expendable jammer and test apparatus	13
8. Model unattended expendable jammer	14
9. Test yos	15

TABLE

1. Test Results of Despin of Model Unattended Expendable Jammer for Brass-Weighted and Aluminum-Weighted Yos	17
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SYMBOLS

a	Jammer radius (in.)	M ₂	Total weight of masses attached to cords (lb _F)
A	Cross-sectional area of cord (in. ²)	P	Breaking strength of cord (psi)
D	Density of cord (lb _F /in. ³)	R	Ratio of initial to final spin velocities
F _{max}	Maximum tensile force on cord (lb _F)	t	Time required for fully unwound cord to change position from tangential to perpendicular to jammer (s)
F ₁	Tensile force on cord while cord is tangential to jammer (lb _F)	T	Time required to despin from initial to final spin velocity (s)
F ₂	Tensile force on cord while cord is changing position from tangential to perpendicular to jammer (lb _F)	\dot{W}	Time rate of change of jammer spin velocity (s ⁻²)
g	Acceleration of gravity (32.2 ft/s ²)	W ₀	Jammer initial spin velocity (rps)
I	Jammer moment of inertia (slug-ft ²)	W ₁	Jammer final spin velocity (rps)
l	Instantaneous length of partially unwound cord (in.)	X	Function of time required for fully unwound cord to change position from tangential to perpendicular to jammer (= W ₀ t)
L	Length of fully unwound cord (in.)	$\dot{\gamma}$	Time variation of angle γ (s ⁻¹) (fig. 3)
M	Effective total weight of cords and attached masses (lb _F)	$\dot{\theta}$	Time variation of angle θ (s ⁻¹) (fig. 3)
M ₁	Weight of each cord (lb _F)		

ENGLISH TO METRIC CONVERSION

English unit	Metric unit
1 in.	2.54 cm
1 ft	0.305 m
1 lb	0.454 kg (force)
1 psi	6.90 kPa
1 slug	0.454 kg (mass)

1. INTRODUCTION

Six unattended expendable jammers (UEJ's) are placed within the interior of a 155-mm shell. The shell is fired as ordinary ordnance over a wide range of trajectories, and each UEJ is ejected from the rear of the airborne shell at a minimum altitude of 3300 ft with a forward speed of up to 2500 ft/s and a spin rotation of up to 260 rps. A controlled spacing of 1600 ± 300 ft between landed units is desired, and each UEJ is required to land on a specified side with its spin axis to within 20 deg of the ground vertical. The angle between the plane of rotation of a highly spinning UEJ and the ground vertical remains essentially unchanged during descent. Consequently, proper landing orientation requires despinning the UEJ to nearly zero spin.

The UEJ can be despun to zero spin by using an angular momentum transfer device, such as a yo-yo. In this procedure, the rotational energy and the angular momentum are conservatively transferred from the UEJ to two small masses ejected from the outer casing of the UEJ. For some trajectories, the allowable time for despin is less than 10 s. The UEJ can be completely despun from any initial spin in less than 1 s with the same ejected masses.

The conservation equations for rotational energy and angular momentum for the system consisting of a UEJ and a yo-yo provide exact solutions for the ratio of final to initial angular velocities and the time to despin in terms of the yo-yo mass ejection system and physical characteristics of the UEJ. Test data of despin of a model of the UEJ are in excellent agreement with predicted data for a known moment of inertia of the UEJ.

2. THEORETICAL CONCEPTS

The yo-yo consists of two identical yos each having a mass, $M_2/2$, attached to one end of a cord of uniformly distributed mass and weight, M_1 . The other end of each cord is attached to the UEJ. The cords are initially wrapped

around the mass center of the UEJ and spin axis, as shown in figure 1. The two cords are attached to the UEJ at diametrically opposed positions to avoid unbalanced forces. When the two masses are simultaneously allowed to unwind about the spinning body, centrifugal force pulls each mass away from the body.

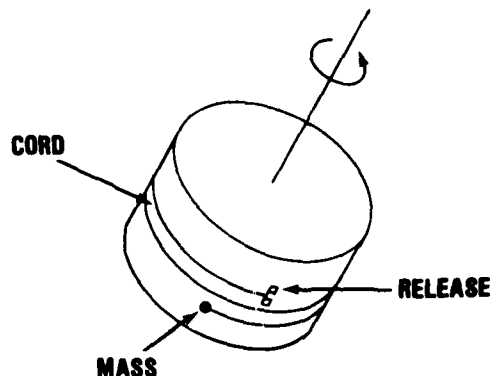


Figure 1. Yo-yo despin device and unattended expendable jammer before despinning.

The cords unwind to their full length, and when each cord attains the position normal to the tangent drawn to the surface of the UEJ as shown in figure 2, each cord is simultaneously released and allowed to escape. Rotational energy and angular momentum are conserved. Hence, the reduction of rotational energy and angular momentum of the spinning UEJ equals the rotational energy and angular momentum imparted to the two cords and masses. The two equations for rotational energy and angular momentum are solved simultaneously to obtain explicit solutions for despin, maximum cord tension, and time for despin as functions of the length and the mass of the yos and the radius and the moment of inertia of the UEJ.

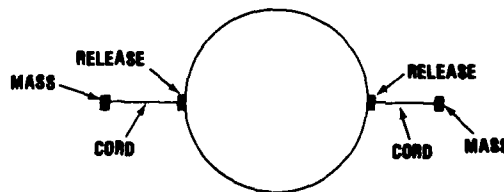


Figure 2. Yo-yo despin device and unattended expendable jammer at time of release of yos.

Following the procedure described by Fedor¹ and referring to figure 3, when $\theta - \gamma = 0$ (which is the position at which the yo is released), conservation of rotational energy is given by

$$\begin{aligned} \frac{IW_1^2}{2} + \frac{M}{2} (aW_1 + L\dot{\gamma})^2 &= \text{constant} \\ &= \frac{1}{2} (I + Ma^2) W_0^2, \end{aligned} \quad (1)$$

and conservation of angular momentum is given by

$$\begin{aligned} IW_1 + M(L + a)(aW_1 + L\dot{\gamma}) &= \text{constant} \\ &= (I + Ma^2) W_0. \end{aligned} \quad (2)$$

where

- a = jammer radius (in.),
- I = jammer moment of inertia (slug-ft²),
- L = length of fully unwound cord (in.),
- M = effective total weight of cords and attached masses (lb_F),
- W_0 = jammer initial spin velocity (rps),
- W_1 = jammer final spin velocity (rps),
- $\dot{\gamma}$ = time variation of angle γ (s⁻¹).

For $G = 144g(1 - R)I/Ma^2 \gg 1$, the simultaneous solution of the two equations yields the ratio of final to initial spin velocities,

$$R = \frac{1 + \frac{Ma^2(1 - L_0)}{144g}}{1 + \frac{Ma^2L_0}{144g}}, \quad (3)$$

where

$$L_0 = [(L/a) + 1]^2.$$

¹J. V. Fedor, *Theory and Design Curves for a Yo-Yo De-Spin Mechanism for Satellites*, National Aeronautics and Space Administration Technical Note D-708 (August 1961).

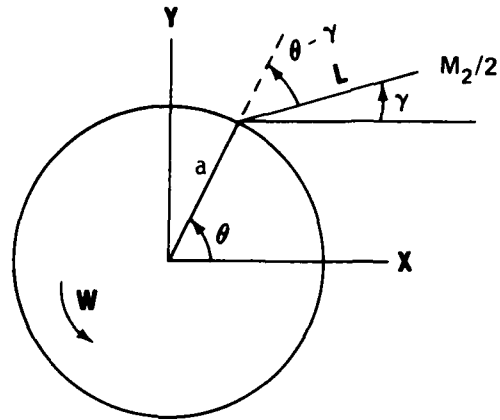


Figure 3. Notation for energy and momentum conservation equations.

According to equation (3), by varying M and L , R may range between $-1 < R \leq 1$. $R < 0$ corresponds to a reversal of the direction of spin. Spin reversal occurs when the yo's mass or length or both are sufficiently large to cause complete despin of the UEJ before the yo's are released from the UEJ. Thereafter, the tension on the cords caused by the centrifugal force exerted by the yo's produces the reversal of the direction of spin of the UEJ.

The tension on a cord during the unwinding of the cord and during which time the cord remains tangential to the UEJ is the product of the mass of the weight and the acceleration:

$$F_1 = -\frac{M}{2} (a\dot{W} + l\dot{\theta}^2),$$

where

- F_1 = tensile force on cord while cord is tangential to jammer (lb_F),
- l = instantaneous length of partially unwound cord (in.),
- \dot{W} = change of jammer spin velocity with respect to time (s⁻²),
- $\dot{\theta}$ = time variation of angle θ (s⁻¹).

The maximum tension occurs when the cord has unwound by the amount $l = \lambda/\sqrt{3}$, and

$$F_{1\max} = 0.65MW_0^2 \lambda (1 - a^2/\lambda^2) \quad (4)$$

where

$$\lambda^2 = (1/M) + a^2.$$

The tension on a cord while the cord is changing position from tangential to perpendicular to the jammer is

$$F_2 = \frac{M}{2} (aW^2 + L\dot{\gamma}^2).$$

The maximum tension occurs at the point of attachment to the jammer, when $\theta - \gamma = 0$, and is

$$F_{2\max} = \frac{MW_0^2 L}{24g} \left\{ \frac{aR^2}{L} + \left[\frac{G + 1 - R(\frac{L}{a} + 1)}{(\frac{L}{a} + 1)(\frac{L}{a})} \right]^2 \right\} \quad (5)$$

When $R \approx 0$, the time required to despin from initial to final spin velocity is

$$T = \frac{L}{aW_0} + \frac{X}{W_0} \quad (6)$$

In equation (6), the first term is independent of R and is the time required for the cord to completely unwind to length L . The second term, X/W_0 , is the additional time required for the fully unwound cord to change position from tangential to perpendicular to jammer, or the additional time required for the cord to release from the jammer. The term X/W_0 is the time, t , required for

$$\int_0^t (\dot{\gamma} - \dot{\theta}) dt = \pi/2,$$

where $t = 0$ denotes the time at which the cord is initially fully unwound.

For large spin reductions and cords with a uniformly distributed mass, as shown by Fedor,¹ the effective mass is

$$M = 2M_1/3 + M_2 \quad (7)$$

¹J. V. Fedor, *Theory and Design Curves for a Yo-Yo De-Spin Mechanism for Satellites*, National Aeronautics and Space Administration Technical Note D-708 (August 1961).

High strength-to-weight cords, such as Kevlar, are essential because of the large tensile forces. Cords made of Kevlar may be assumed to have a breaking strength of $P = 3(10^5)$ psi and a density in the range of $0.06 \leq D \leq 0.12$ lb_F/in.³. Allowing for a 20-percent safety margin, the minimum cross-sectional area is

$$A = F_{\max}/2.5(10^5) \quad (8)$$

and the maximum length of each cord is

$$L = M_1/AD \quad (9)$$

The above equations have been solved on a computer. Figure 4 summarizes the predicted relations for R as functions of M_1 , L , A , $F_{1\max}$, and $F_{1\max}/F_{2\max}$ in the range $-0.2 \leq R \leq 0.4$ for several values of M_2 , with $W_0 = 300$ rps, $I = 0.0108$ slug-ft², $P = 2.5(10^5)$ psi, and $D = 0.06$ lb_F/in.³. Thus, various combinations of values of L , M_1 , and M_2 can be used to obtain a given value of R , including spin reversal for which $R < 0$. For example, from figure 4(a,b), we see that the UEJ can be completely despun from any initial spin with $L = 15$ in., $M_1 = 0.062$ lb_F, and $M_2 = 0.12$ lb_F. The maximum tensile force on the cord is $F_{1\max}$ and amounts to about 17,000 lb (fig. 4d, e). By equation (6), the time required for the cord to unwind is 3.2 ms and $X/W_0 \approx 1$ ms. For a given R , the effect of increasing M_2 is to shorten L and increase $F_{1\max}$. For given R and M_2 , the ratio of changes between M_1 and I is

$$\frac{dM_1}{M_1} \frac{dI}{I} = 1$$

and between $F_{1\max}$ and I is

$$0 < \frac{dF_{1\max}}{F_{1\max}} \frac{dI}{I} < 1$$

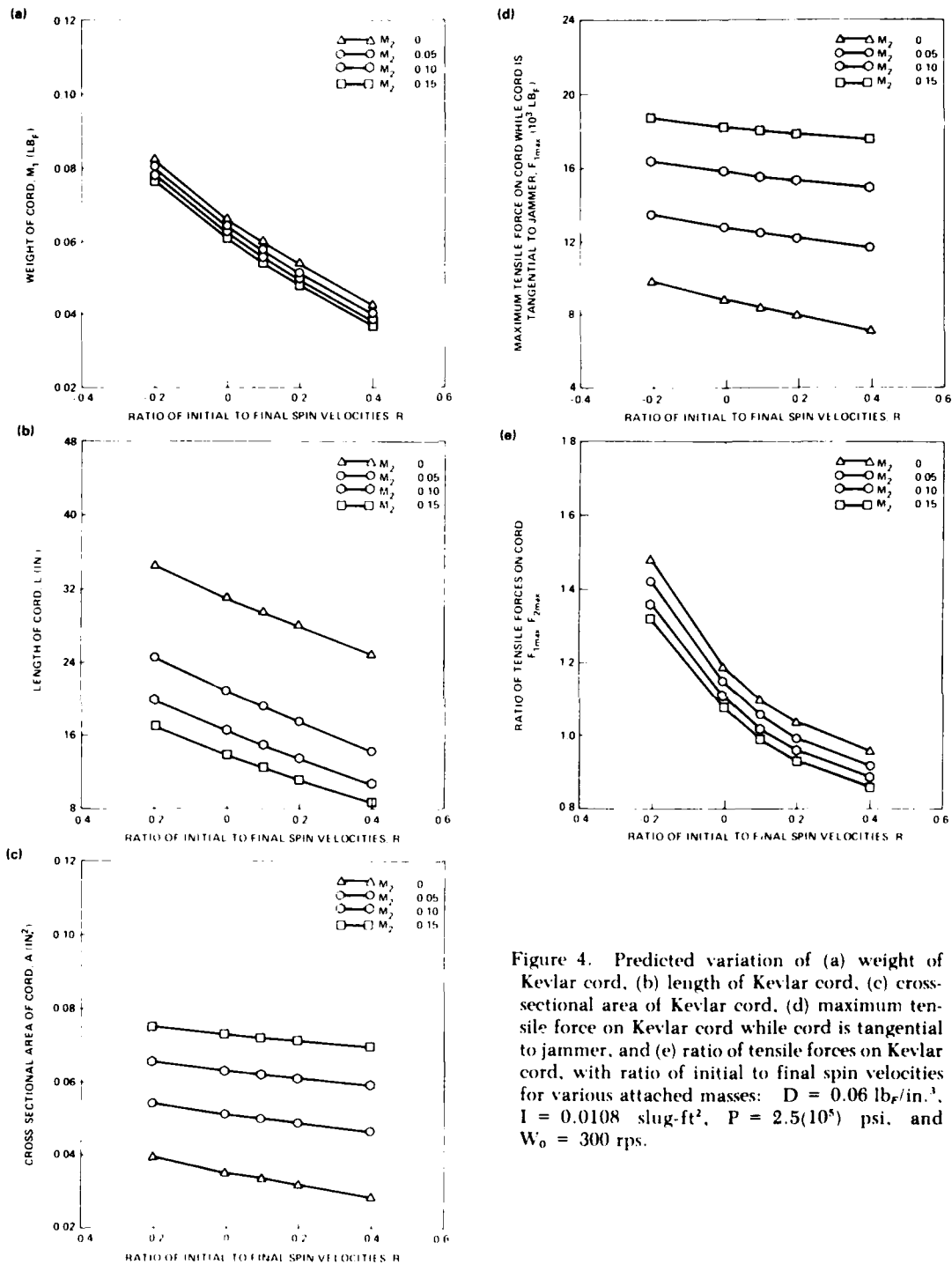


Figure 4. Predicted variation of (a) weight of Kevlar cord, (b) length of Kevlar cord, (c) cross-sectional area of Kevlar cord, (d) maximum tensile force on Kevlar cord while cord is tangential to jammer, and (e) ratio of tensile forces on Kevlar cord, with ratio of initial to final spin velocities for various attached masses: $D = 0.06 \text{ lb}_F/\text{in.}^3$, $I = 0.0108 \text{ slug-ft}^2$, $P = 2.5(10^5) \text{ psi}$, and $W_0 = 300 \text{ rps}$.

The dependency for all relations on P and D enters only in the ratio P/D . The above relationships are repeated in figure 5 for a change in cord density to $D = 0.12 \text{ lb}_f/\text{in}^3$. The dependency of the various functions on D is shown in figure 6 for $R = 0$ and $P = 2.5(10^5) \text{ psi}$. From the latter, we see that a

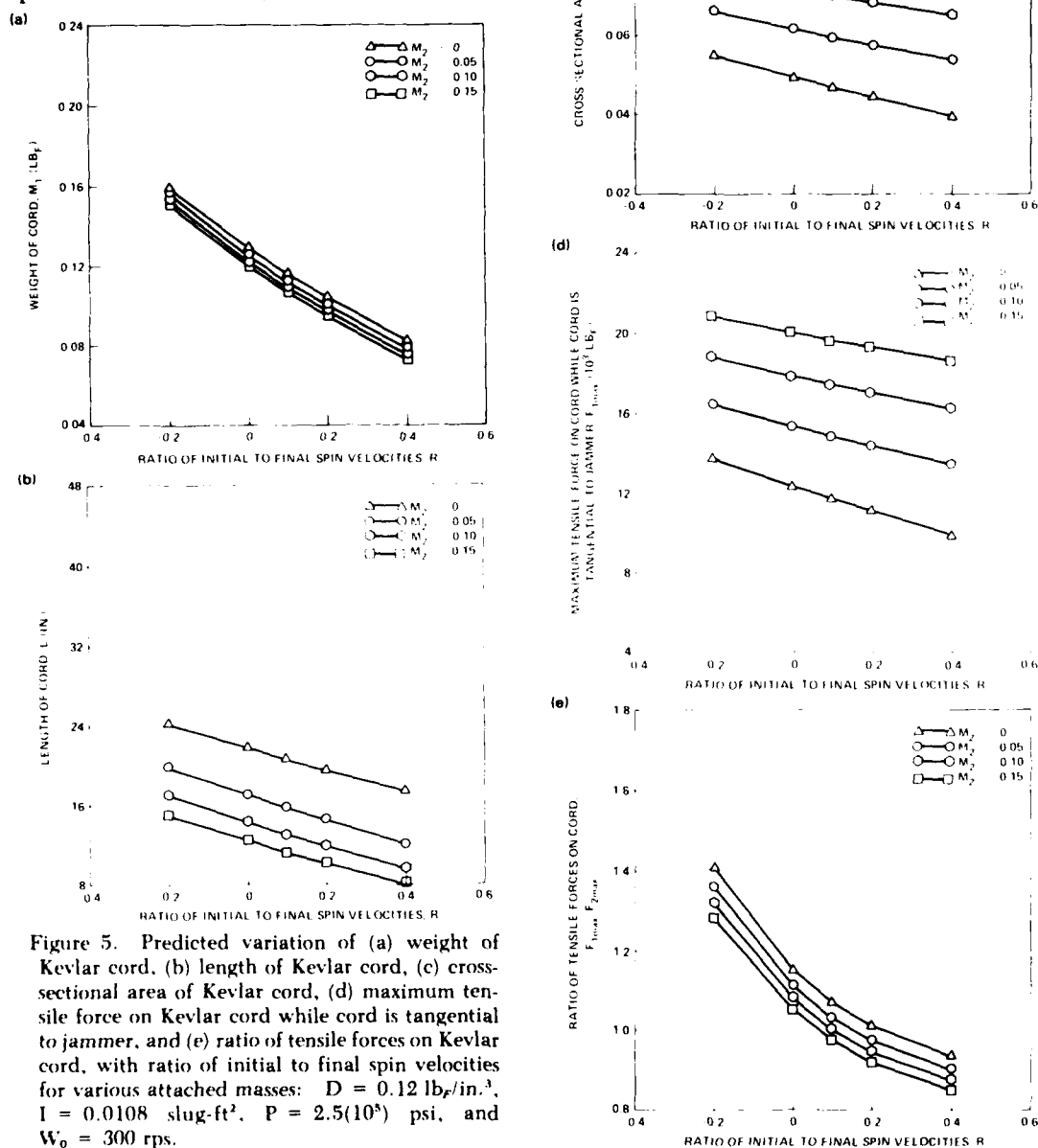


Figure 5. Predicted variation of (a) weight of Kevlar cord, (b) length of Kevlar cord, (c) cross-sectional area of Kevlar cord, (d) maximum tensile force on Kevlar cord while cord is tangential to jammer, and (e) ratio of tensile forces on Kevlar cord, with ratio of initial to final spin velocities for various attached masses: $D = 0.12 \text{ lb}_f/\text{in}^3$, $I = 0.0108 \text{ slug-ft}^2$, $P = 2.5(10^5) \text{ psi}$, and $W_0 = 300 \text{ rps}$.

primary effect of increasing the strength-to-weight ratio of the cord material is to permit a lengthening of the cords, which in turn permits a reduction of M and a reduction of the maximum force on the cord. Similar results pertain for other R in the range $-0.2 \leq R \leq 0.4$.

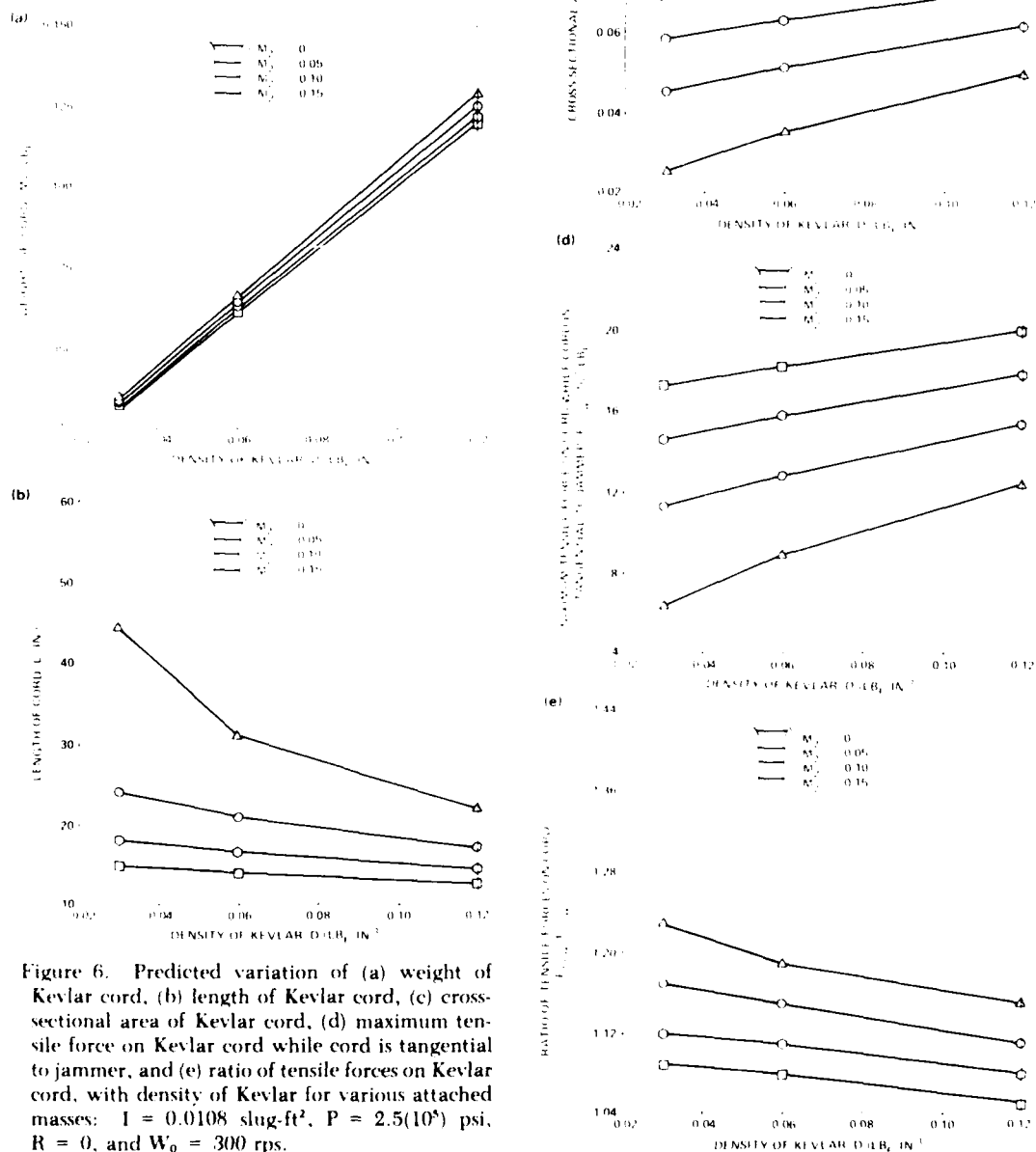


Figure 6. Predicted variation of (a) weight of Kevlar cord, (b) length of Kevlar cord, (c) cross-sectional area of Kevlar cord, (d) maximum tensile force on Kevlar cord while cord is tangential to jammer, and (e) ratio of tensile forces on Kevlar cord, with density of Kevlar for various attached masses: $M_1 = 0.0108$ slug-ft², $P = 2.5(10^4)$ psi, $R = 0$, and $W_0 = 300$ rps.

The following example is given to indicate the required values and tolerances of L and M to despin a typical UEJ. For a single yo-yo (a single pair of yos) and $W_0 = 300$ rps, successful despin of the UEJ to within a final spin of ± 15 rps requires a value of R in the range $-0.05 \leq R \leq 0.05$. For $D = 0.06$ and $M_2 = 0$, the associated ranges of L and M_1 are $32.0 \leq L \leq 30.3$ in. and $0.070 \leq M_1 \leq 0.063$ lb_F (fig. 4b,a). These tolerances are easily met in mass-produced items. Assuming good repeatability, a single yo-yo will accomplish the required despin.

3. EXPERIMENTAL APPARATUS

The experimental apparatus used to demonstrate the feasibility of a single yo-yo system for despinning the UEJ consisted of a single pair of yos attached to a test model UEJ, a detonator and a detonating cord to initiate unwinding of the yos, an electric motor to spin the UEJ to about 60 rps, and a mechanism for disengaging the motor from the UEJ so as to allow the UEJ to rotate freely on a shaft following disengagement (fig. 7, 8).

A framing camera with speeds ranging between 2300 and 2900 frames/s was used to measure the times required to sever the Kevlar cords, despin the UEJ, and release the cords from the UEJ. The above times were determined with a precision of one frame, or ± 0.4 ms. The camera speed is known to an accuracy of within 10 frames/s. A tachometer was used to obtain spin records of the UEJ. The tachometer measured spin to a precision of within 1 percent of the instantaneous spin.

The yos used in the tests consisted of Kevlar cords attached at one end to either a brass weight or an aluminum weight and the other end to a steel link (fig. 9). For each test, the link end of each of the two yos was joined to the UEJ at the release hook; the two release hooks were located at diametrical ends of the UEJ. Each of the cords was wrapped about the circumference of the UEJ in a plane approximating that of its center of mass. The weights were fitted into wells of the UEJ and held securely in place by a restraining screw at the

end of each cord. The cross section of the cords was 0.10×0.25 in.². The total length of each cord was 17.5 in. To an accuracy of within ± 2 percent, the cord lengths between the point of applied force to the UEJ and the midpoint of the weights was 14.1 and 13.8 in. for each of the brass- and aluminum-weighted yos. The weights of the link and of the collar with pin were 0.021 and 0.017 lb. The weights of the Kevlar cords for the brass- and aluminum-weighted yos were 0.013 and 0.014 lb. The brass and aluminum weights were each 0.077 ± 0.001 and 0.029 ± 0.001 lb. Thus, each brass yo consisting of link, collar with pin, cord, and weight weighed 0.128 ± 0.001 lb. Each aluminum yo, similarly constructed but without collar and pin, weighed 0.064 ± 0.001 lb.

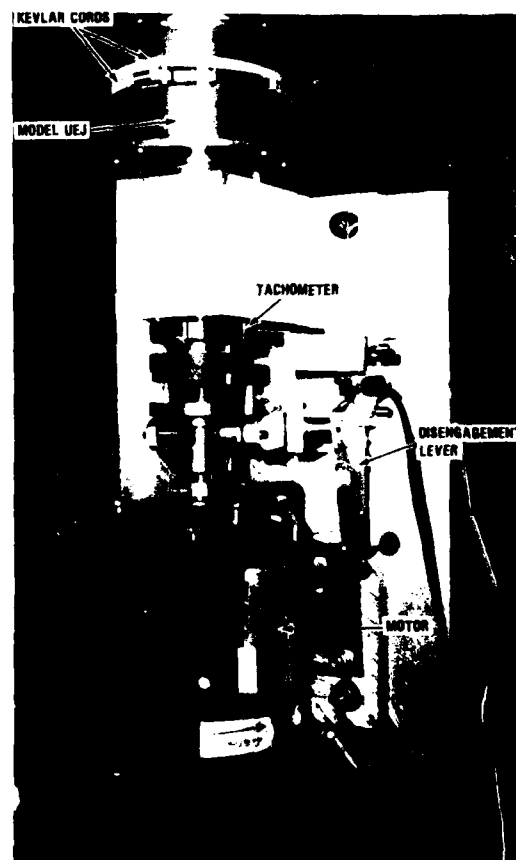


Figure 7. Model unattended expendable jammer (UEJ) and test apparatus.

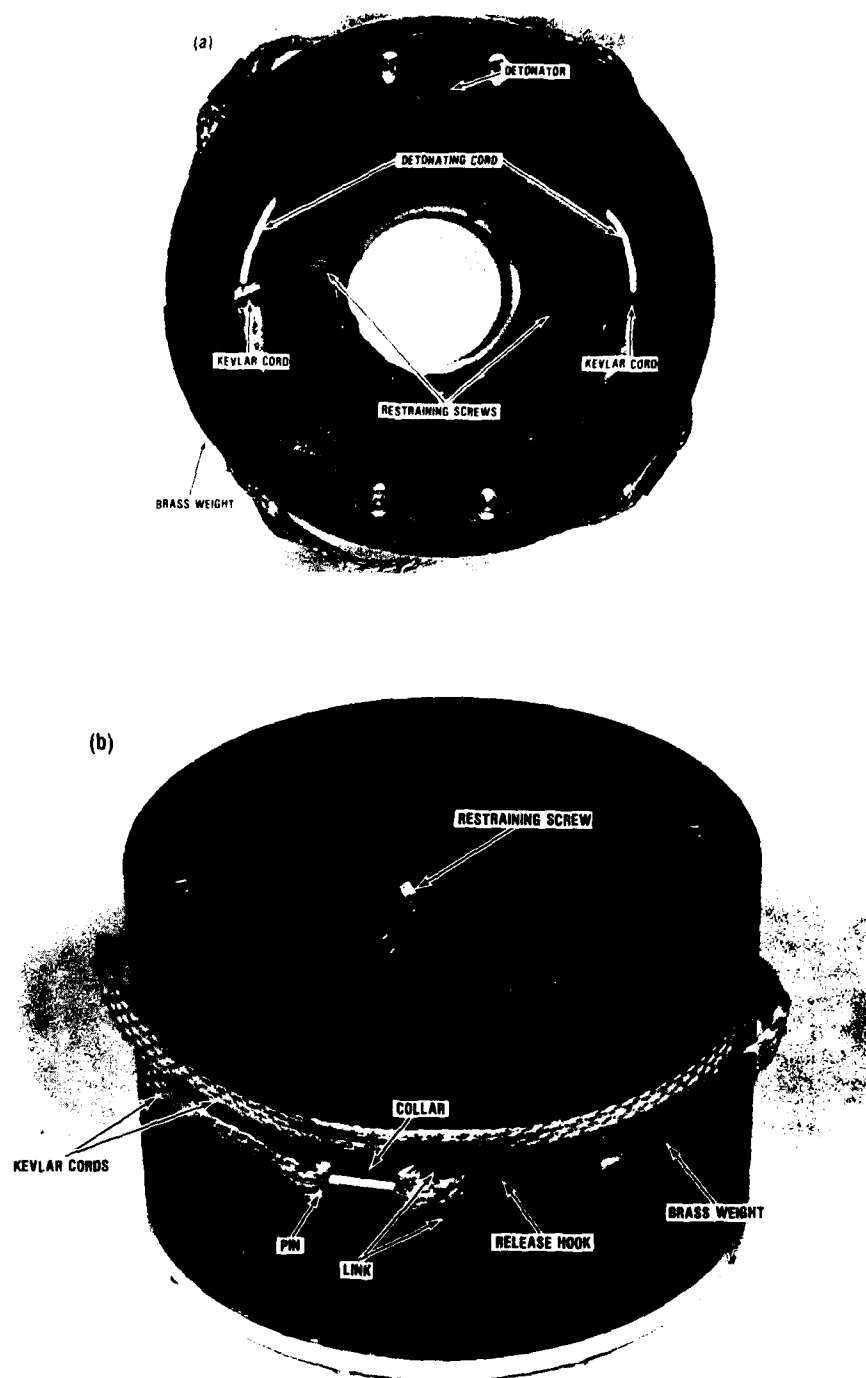


Figure 8. Model unattended expendable jammer: (a) top and (b) front and top.

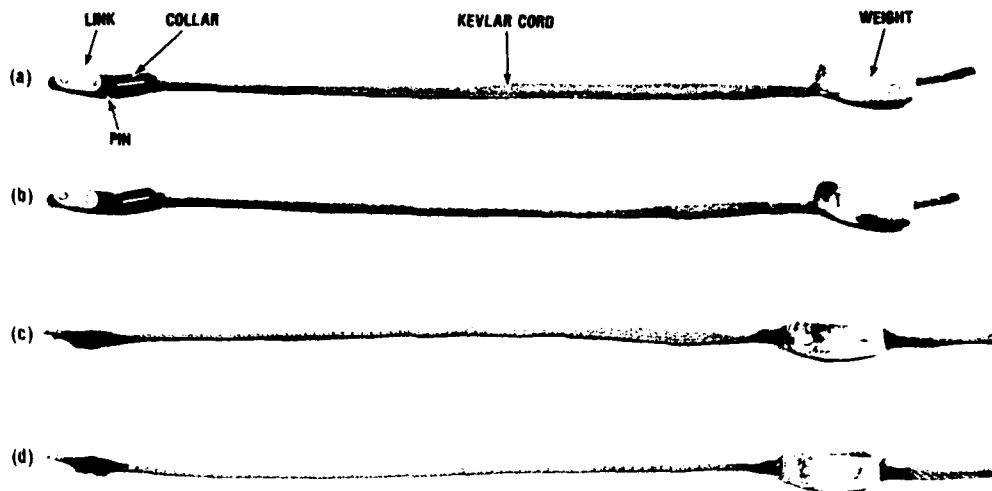


Figure 9. Test yos: (a, b) complete brass weighted and (c, d) aluminum weighted (links not shown).

Twelve tests were performed, eight with a pair of brass yos and four with a pair of aluminum yos. Except for the above noted slight variations in the lengths and the weights of the yos, the tests of each of the brass- and each of the aluminum-weighted yos were identical.

The test model UEJ weighed 7.6 lb. The rotating shaft to which it was fixed in addition to other attachments free to rotate following disengagement from the motor weighed 1.3 lb. Hence, the total weight of the rotating ensemble following disengagement was 8.9 lb. The radius of gyration of this ensemble was estimated at 2.0 in. The radius of gyration was calculated from equation (3) for both the brass- and aluminum-weighted yos following completion of the tests, by using the test values found for the despin. The radius of gyration was found to average 1.94 and 1.91 in. for the brass- and aluminum-weighted yos. In the latter two calculations, the values used for M_1 and M_2 were the cords and the metal weights; the weights of the link and of the collar with pin were not included.

The despin time of the UEJ for a yo-yo system consisting of a single pair of yos for most practical applications will amount to between 3 and 30 ms. The difference in time between the release of the two yos must be much smaller than the time for despin in order to avoid lateral displacement and random dispersion of the UEJ in a direction normal to the UEJ spin axis. This required difference in release time decreases with increasing W_0 because of the larger forces encountered by the cords with larger W_0 . To attain the required "simultaneity" in the time of release of between 0.3 and 3 ms, a single detonator was placed at the midpoint of a semicircle of diameter 3.5 in. of mild detonating cord* (fig. 8). Each end of the detonating cord was placed in physical contact with a section of the Kevlar cord between the restraining screw and the weight. Ignition of the detonating cord caused the severance of the ends of the Kevlar cords that restrained the weights. The speed of detonation of the detonator cord was 25,000 ft/s, and the consequent severance of the Kevlar cords was

*The Navy BBU-7 detonator and HMX/FLSC detonating cords (9 grains ft) were used in the reported tests.

calculated to begin about $10 \mu\text{s}$ following initiation of detonation. The difference between travel times for the detonation to reach the two ends of the Kevlar cords was measured as $1 \mu\text{s}$.

4. THEORETICAL AND EXPERIMENTAL RESULTS

Equation (3) was used to obtain the design requirements (lengths and weights) for the brass- and aluminum-weighted yos so as to obtain specified values of R , by using an estimated radius of gyration of 2.0 in. for the disengaged freely rotating ensemble of 8.9-lb weight (which includes the model UEJ, the shaft, the tachometer, etc.). By equation (3), R is independent of W_0 . Equations (5) to (7) were used to obtain predicted values of $F_{1\text{max}}$, $F_{2\text{max}}$, and T for an assumed initial spin of 60 rps. The values for $F_{1\text{max}}$ and $F_{2\text{max}}$ were used to determine the required strength of the Kevlar cords. The time required to despin (starting from severance of the cords to their release from the UEJ) was calculated to be 22 ms for $L = 14.0$ in. and $W_0 = 55$ rps. Here, $L/aW_0 = 16$ ms and $X/W_0 = 6$ ms. The value of X is dependent on R , but is independent of W_0 . The value of X was calculated from the momentum and energy equations by successive integrations for $\dot{\gamma}$ from $\theta - \gamma = \pi/2$ to $\theta = \gamma$.

The results of the 12 tests are summarized in table 1. These results were anticipated from the calculations by using an approximate value for I . It is important to observe that, had the precise value for I been known, the agreement between the calculated and test data for W_1 would have been the same as the test repeatability cited below.

In the tests of the eight brass-weighted yos, the average measured W_0 was 52.1 rps. Here, the average measured R was -0.125 with the maximum deviation in R of 0.013. With this precision, the corresponding maximum deviation in W_1 is 0.67 rps.

In the tests of the four aluminum-weighted yos, the average measured W_0 was 54.5 rps. In tests 2, 3, and 5, the average measured R was 0.296, with the maximum deviation in R of only 0.006. With this precision, the corresponding maximum deviation in W_1 is 0.33 rps. One of the recovered links was separated from a yo in test 1. R measured 0.360 in this test, and separation of the link during despin would cause the observed larger value of R .

Assuming the above repeatability in R of within 0.013 for spins up to the required maximum of 260 rps, a single pair of yos could completely despin the UEJ to within ± 3 rps.

Clear camera data were recorded in 10 of the 12 tests. As shown in table 1, the test values of T (measured from the instant of detonation to the release of the two yos) for the brass- and aluminum-weighted yos were 18 ± 1 and 20 ± 2 ms. The Kevlar cords were observed to completely sever in 1.0 to 1.5 ms following detonation. The observed difference between the release times of the two yos from the model UEJ was usually less than 1.0 ms and ranged between 0 and 1.4 ms.

The forces occurring during despin vary as W_0^2 . The forces $F_{1\text{max}}$ and $F_{2\text{max}}$ exerted on the UEJ also depend on the yo-yo design itself and are about 11,000 lb at $R = 0$ and $W_0 = 260$ rps. A structurally sound yo-yo may be constructed solely of Kevlar cords of sufficient mass and length. The single pair of yos can apply for all W_0 since R is independent of W_0 . The design parameters M_1 and L for such a pair of yos are indicated in figure 6(a, b) for $R = 0$ by the curves with $M_2 = 0$.

5. SUMMARY AND CONCLUSIONS

Twelve tests performed in a laboratory demonstrated that a single pair of yos will completely despin a model of the UEJ of 8.9-lb weight and 1.9-in. radius of gyration with an initial spin of 57 rps in a time period of 20 ms. To completely despin, each yo weighed 0.13 lb and was 14 in. long. The time required for despin varies inversely with the initial spin.

TABLE 1. TEST RESULTS OF DESPIN OF MODEL UNATTENDED EXPENDABLE JAMMER
FOR BRASS-WEIGHTED AND ALUMINUM-WEIGHTED YOS

Weight	Test	Jammer spin velocity (rps)		W_0/W_1	Despin time (ms)	Remarks
		Initial, W_0	Final, W_1			
Aluminum	1	54.6	19.7	0.360		Link is believed to have separated from one yo during despin.
	2	54.3	16.4	0.302	23	
	3	54.2	15.9	0.294	24	
	5	54.8	16.0	0.292	20	
Brass	4	54.9	-6.49	-0.118	19	No test was done.
	6	55.4	-6.27	-0.113	18	
	7	55.6	-6.91	-0.124	17	
	8	—	—	—	—	
	9	56.3	-7.78	-0.138	18	
	10	57.0	-6.83	-0.120	19	
	11	56.5	-7.35	-0.130	17	
	12	55.5	-6.92	-0.125	17	
	13	—	—	—	—	
	14	—	—	—	—	
	15	50.5	-6.56	-0.130		

The observed difference between the release times of the two yos from the model UEJ was usually less than 1 ms. Translation of the UEJ caused by this difference in release times is well within the allowable 300-ft ground dispersion.

The experimental repeatability of the ratio of the final spin to the initial spin was found to correspond to a repeatability of the final spin to within 0.67 rps for initial spins ranging

between 50 and 57 rps. By scaling the above repeatability, a single pair of yos could despin the UEJ to within ± 3 rps of zero spin at any initial spin up to 260 rps.

Calculations show that a single pair of yos can be used to completely despin the UEJ with each yo consisting solely of a Kevlar cord (without weight attached thereto) for initial spins up to 260 rps.

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